

LOW VOLTAGE DC TO DC CONVERTER-REGULATOR
WITH MINIMUM EXTERNAL MAGNETIC FIELD DISTURBANCE

REPORT NO. 1,

Contract Number NAS 5-3899

National Aeronautics and Space Administration

First Quarterly Progress Report

1 June 1964 to 30 August 1964

Goddard Space Flight Center
Greenbelt, Maryland

Submitted by
Honeywell Inc.
Ordnance Division
Hopkins, Minnesota

Serial No. 68741

Copy _____ of _____

FACILITY FORM 802	N65-22172	
	(ACCESSION NUMBER)	(THRU)
	56	1
	(PAGES)	(CODE)
	CR-62352	03
	(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

GPO PRICE \$ _____

OTS PRICE(S) \$ _____

Hard copy (HC) 3.00

Microfiche (MF) .50

Honeywell



A DIVISION OF THE
MILITARY PRODUCTS GROUP



LOW VOLTAGE DC TO DC CONVERTER-REGULATOR
WITH MINIMUM EXTERNAL MAGNETIC FIELD DISTURBANCE

REPORT 1

Contract Number NAS 5-3899

National Aeronautics and Space Administration

First Quarterly Progress Report
1 June, 1964 to 30 August, 1964

OBJECT: The object of this contract is to design and develop a low voltage dc to high voltage dc converter-regulator with minimum external magnetic field disturbance. This device will efficiently convert the inherently low voltages of newly developed energy sources to useful higher regulated voltages and provide more reliable power systems for space applications which also have a requirement for minimum external magnetic field disturbance.

Prepared by: John T. Lingle
John T. Lingle
Project Engineer

Approved by: H. T. Mooers
H. T. Mooers
Project Supervisor

Ken Jenson
Development Engineer

W. K. Maenpaa
Section Chief W. K. Maenpaa

Submitted by
Honeywell Inc.
ORDNANCE DIVISION
Hopkins, Minnesota



TABLE OF CONTENTS

	<u>Page</u>
SECTION I PURPOSE	1
SECTION II SUMMARY	2
SECTION III CONFERENCES	4
SECTION IV PROJECT DETAILS	5
A. Procurement of Material	5
B. Coaxial Converter Design	6
1. Oscillator Assembly	9
C. Transformer Design	10
D. Choke Coil Design	11
E. Investigation of Methods to Improve Regulator Performance	13
1. Computer Programming	16
F. Power Oscillator Operating Frequency Studies	17
SECTION V CONCLUSIONS	22
SECTION VI PROGRAM FOR THE NEXT QUARTER	25
SECTION VII IDENTIFICATION OF PERSONNEL	26
APPENDIX A CALCULATION OF THE EXTERNAL MAGNETIC FIELD DISTURBANCE AROUND A CHOKe COIL WITH A TOTALLY ENCLOSED COIL AND AIR GAP	



LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Coaxial Power Oscillator	7
2	Choke Coil Flux Paths	12
3	Voltage Regulator Circuit	14
4	Experimental Two Feedback Transformer Power Oscillator Circuit	20
5	Choke Coil External Magnetic Moment	A-2
6	Equivalent Magnetic Circuit	A-7
7	Calculation of the Magnetic Field Around a Single Section Choke Coil	A-11
8	Dual Section Choke Coil Oriented with External Fields Bucking	A-15
9	Geometrical Construction for Calculation of the External Magnetic Field of a Dual Section Choke	A-17



SECTION I

PURPOSE

The purpose of this contract is to design and to develop an efficient, reliable, and lightweight, transistor low voltage dc to high voltage dc converter with minimum external magnetic field disturbance for space applications. The converter will be designed to convert the output of fuel cells, thermionic diodes, thermoelectric generators, solar cells, and high performance single cell electrochemical batteries to a regulated 28 volt dc output. The program includes circuit optimization and new design efforts to reduce external magnetic field disturbance, size, and weight. Effort will be directed toward construction of a model and magnetic field measurements to verify that the design has been optimized to meet the performance requirements and design goals.



SECTION II

SUMMARY

During this initial quarter, the effort has been directed toward analytical analysis of magnetic field disturbance problems, design and layout of a coaxial oscillator, design of transformers, investigation of circuit improvements, and procurement of material.

Magnetic field disturbance calculations on a choke coil design have established that a single-section choke with the coil and air gap totally enclosed by the cup type mu-metal core will produce a 1.32 gamma magnetic field disturbance at 18 inches. This is 66 percent of the specified 2 gamma allowable maximum. The external magnetic field disturbance can be reduced to approximately 4 percent of the maximum specification requirement by the use of a dual section choke oriented in a bucking arrangement.

A coaxial oscillator has been designed with emphasis on ease of assembly. Fabrication of this unit will begin shortly. Transformers and other magnetic components have been designed utilizing the high permeability core materials required for external magnetic field suppression.

Investigation of circuit improvements has resulted in several changes in the regulator section to reduce the required number of parts and to improve reliability, efficiency, and temperature stability. Methods of improving the switching speed of the power oscillator are being investigated, and initial experiments have shown promise. Further work will determine the magnitude of the advantages that can be obtained by the methods currently under investigation. A circuit stress analysis is underway, and parameter variation calculations will be programmed on a computer. The current flow through each component will be determined for magnetic field studies.



Emphasis has been placed upon the selection of material and components which will minimize external magnetic field disturbance. Non-magnetic equivalents have been found and ordered for most circuit components. Selection of some of the transistors will take more time because several manufacturers are being consulted. The main oscillator transistors can be fabricated with non-magnetic materials.



SECTION III

CONFERENCES

During this initial quarter, no formal conferences were held. However, Mr. J. T. Lingle from the Honeywell Ordnance Division met Mr. E. Pascuitti from the National Aeronautics and Space Administration-Goddard Space Flight Center on May 20, 1964, at the 18th Annual Power Sources Conference and discussed technical details associated with low input voltage conversion and regulation. Details of this program have been discussed since in telephone conversations between Mr. J. T. Lingle and Mr. E. Pascuitti. It is anticipated that a formal conference on this program will be held in the near future.



SECTION IV

PROJECT DETAILS

A. PROCUREMENT OF MATERIAL

The piece parts and material required for model fabrication have been determined, ordered, and some material has been received. The low external magnetic field disturbance requirements of this program necessitate careful selection of components. Selection of basically non-magnetic components has been emphasized.

The status of the specific components is listed below:

- 1) Transformers and choke coils will be fabricated with "supermalloy" and "mu-metal" cores which have high permeability and low residual flux.
- 2) Tantalum capacitors, having a non-magnetic negative lead, will be used. Welding of a non-magnetic solderable lead to the positive tantalum lead will be investigated. If welding this lead cannot be easily accomplished, the presently available nickel lead will be trimmed as short as possible and used. An order has been placed for capacitors meeting these requirements.
- 3) Orders have been placed for resistors which will have non-magnetic leads.
- 4) Diodes, zener diodes, and high speed diodes, not using any appreciable magnetic materials in their construction, have been ordered.



- 5) Investigation reveals that transistors can be fabricated with a minimum of magnetic materials. The Honeywell MHT 2205 is the prime transistor in the device, and it presently contains only one consequential magnetic part (a copper-cored kovar base lead). This transistor will be primarily non-magnetic when a copper lead identical to that used in the emitter is substituted for the one used in the base. Personnel at the Honeywell Semiconductor Division have stated that they can provide us with transistors having this non-magnetic construction.

Investigation has shown that some of the other required transistors which are commercially available contain various amounts of magnetic materials. It is possible to obtain stainless steel transistor cases, and most of the transistors required might be purchased with non-magnetic containers. We have sent inquiries to various manufacturers to determine the feasibility and cost of obtaining specific transistors in non-magnetic cases. The selection and procurement of transistors to meet these requirements will take additional time. Meanwhile, we intend to select those transistors with lower magnetic material content for the first model.

- 6) Other construction materials will be non-magnetic. The conductors will be fabricated from aluminum and copper. Brass or stainless steel screws will be used for assembly. The structure and outer cover will be aluminum.

B. COAXIAL CONVERTER DESIGN

The low input voltage converter section of this device has been designed with completely coaxial and symmetric primary current paths to minimize external magnetic field disturbance. The coaxial converter, shown on Figure 1, is arranged so that the transformers (T_1 , T_5) and transistors (Q_1 , Q_2 , Q_3 ,

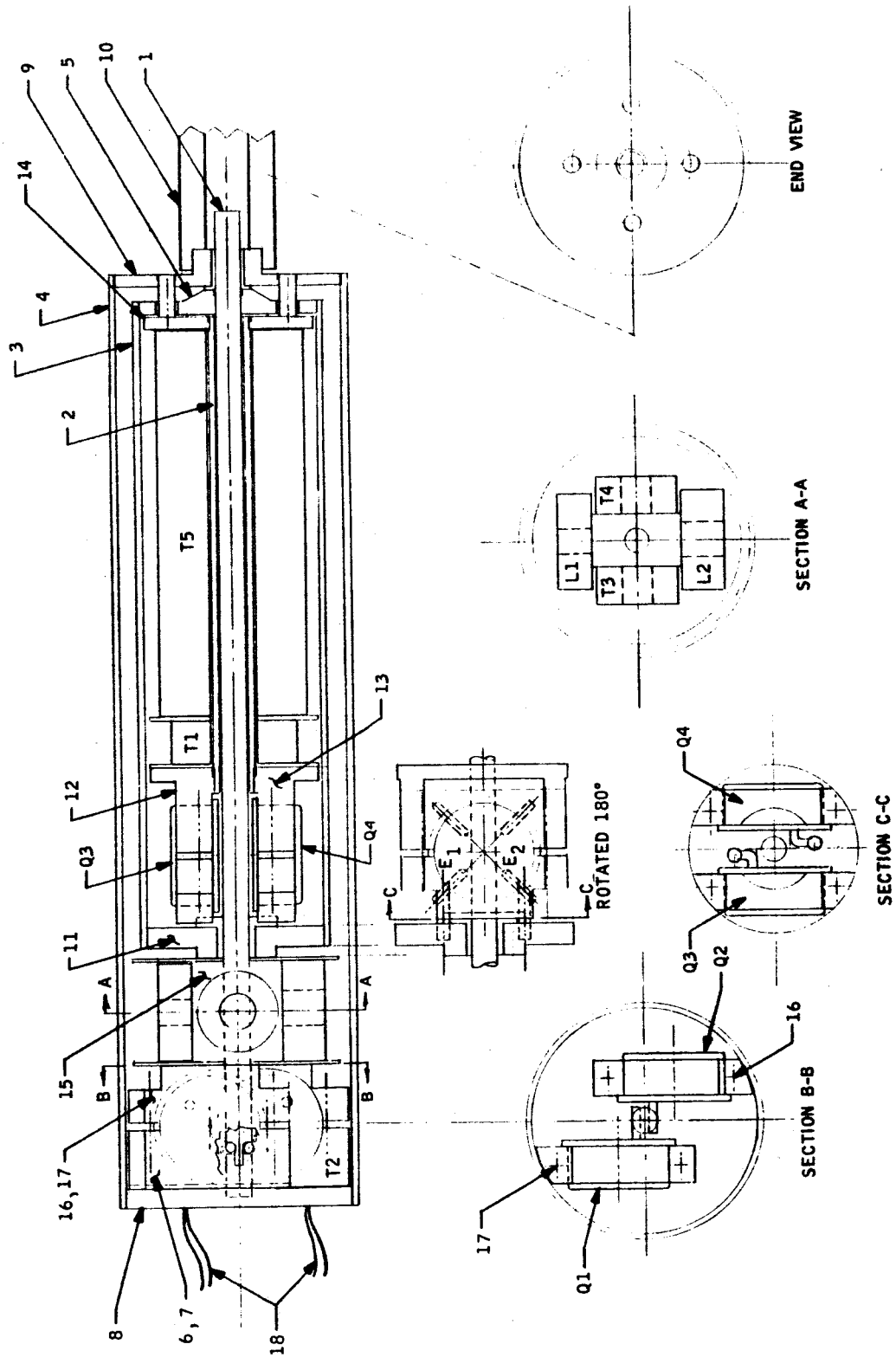


Figure 1 - COAXIAL POWER OSCILLATOR

and Q_4) can be assembled with ease of access to all components before the outer conductor tubes are placed on the device. The current flow paths through the oscillator can be traced as follows: Assuming that transistors Q_1 and Q_2 are rendered conductive, current will flow down conductor (1) through the center of transformers T_1 , T_5 , to the emitter-collector junctions of Q_1 , Q_2 , thus exciting the cores of T_1 , T_5 , and inducing voltages in their secondary windings. The current then flows from the collectors of Q_1 , Q_2 to the transistor clamps (6), (7), through the left end bell (8), the negative outer tubular conductor (4), the right end bell coupling (9), and then back along the outer negative sheath of the coaxial input lead (10).

When transistors Q_3 , Q_4 are rendered conductive, the current flows through the one-turn primary in the opposite direction as follows: Current flows from the positive input lead (1), through the positive junction disk (5), and the positive tubular conductor (3) to the positive disk (11). Current then flows through two tubular pins from the disk (11) to the emitters of transistors Q_3 , Q_4 . From the emitters, the current flow continues through the emitter-collector junction, the transistor clamps (12) (13), and the inner tubular conductor (2), passing through the center of transformers T_1 , T_5 and exciting their cores in the opposite direction.

After emerging from the transformer core through conductor (2), current flows through the negative feedthrough coupling (14) into the negative right end bell (9) and out to the negative input lead (10).

In each case, the current flows through a coaxial lead in the center of the core and a coaxial tube on the outside of the core. The net current flow through the device is zero, and, therefore, the external magnetic field disturbance is theoretically zero. The field generated by one conductor is canceled out by the opposing field of the other conductor. Complete cancellation requires that the conductors must be coaxial and concentric. Calculations have indicated that the concentricity must be held to within 0.003 inch to limit the external magnetic field disturbance to the 2 gamma specification requirement.



1. Oscillator Assembly

The oscillator will be assembled as follows: Transistor clamps (12 and 13) will be fused to conductor (2). Insulation and the wound transformers (T_1 and T_5) will then be slipped onto the conductor assembly (2). The negative feed through coupling (14) is next soldered to conductor (2). Transistors Q_3 , Q_4 will then be secured in clamps (12 and 13). Junction disk (5) is next fused to conductor (1), and the conductor wrapped with glass tape insulation. The conductor is then placed inside tubular conductor (2). Transformer (T_1) secondary leads are soldered to the bases of Q_3 , Q_4 . An insulation bushing and the positive disk (11), with tubular conductor (3) fused to it, are next placed on conductor (1). Drive winding leads from transformer (T_1) are also soldered to disk (11). The emitters of Q_3 , Q_4 are soldered to disk (11) with tubular pins. Next, an assembly containing small miscellaneous magnetic components, fastened to a plastic block (15), is inserted onto conductor (1), and electrical connections between these and the appropriate transformer windings are then made. The right hand halves of transistor clamps (16 and 17) are also secured to block 15 and are an integral part of it. Transistors Q_1 , Q_2 are then inserted in clamp halves (16 and 17), secured with a temporary fixture, and then the emitters of Q_1 , Q_2 are soldered to appropriate slots in conductor (1).

Transformer (T_1) windings are also soldered to conductor (1) and the bases of Q_1 , Q_2 . The temporary holding fixture is then removed; the subassembly consisting of the left end bell (8) and transistor clamp halves (6 and 7) is then inserted onto the transistors and transistor clamp halves (16 and 17) and secured by tightening nuts on studs located in clamp halves (6 and 7). Appropriate circuit leads are brought out through holes in disk (11) and end bell (8) for connection to the voltage regulator and filter circuits. Next, tubular conductor (3) is soldered to junction disk (5). Tubular conductor (4) is slid over the assembly from the right. It is pressed onto left hand end bell (8) to provide an



excellent electrical connection without the need for high temperature soldering. An insulation bushing and the right hand end cap (9) is next inserted over conductor (1). This end cap (9) is then soldered to outer tubular conductor (4) and the pins from the negative coupling disk (14) to complete the coaxial oscillator assembly. Insulation is provided between negative feedthrough disk (14) and the positive junction disk (5) to prevent shorting. A coaxial input lead (10) is then fastened to end bell (9) and insulated from input conductor (1). Connections to the regulator and filter section are then made by leads (18) passing through holes in the left end bell (18).

The above assembly contains soldered joints and press fit joints for excellent electrical contact and easy assembly and disassembly. In final models it will be possible to use welded joints and complete hermetic sealing can be provided if desired. During electrical check out of the initial model, tubular conductors (3) and (4) will be replaced by temporary conductor tubes having large areas cut away so that access can be made to test points for measurement.

C. TRANSFORMER DESIGN

The power transformer has been designed with a supermalloy toroidal core. The primary winding consists of one coaxial turn and has a coaxial return path. The secondary windings will be bifilar wound and evenly distributed around the core to effectively cancel leakage flux. A higher operating frequency of between 1000 and 2500 cps. will be used to minimize the core size and reduce the total magnetic mass.

The feedback transformer is constructed similar to the power transformer and is mounted upon the coaxial one turn primary adjacent to the power transformer. Other transformers will be mounted in close proximity to reduce the effective length of the converter's magnetic dipole.



To minimize leakage flux caused by stray current loops, special attention will be paid to transformer lead dress and to the interconnections between the transformer windings.

Before assembly into the unit, dc currents will be passed through the transformer windings, and the external magnetic field will be mapped with a magnetometer to ensure that the windings are evenly distributed and the external magnetic field due to winding leakage flux is minimized.

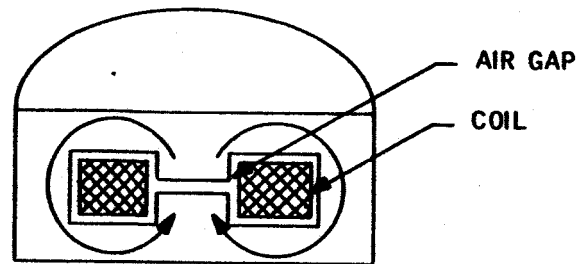
D. CHOKES COIL DESIGN

Practical choke coils contain an air gap to prevent saturation of the iron core. Due to the high permeability of the mu-metal core, practically all of the magnetomotive force is impressed across the air gap. An exposed air gap will, therefore, provide extensive magnetic field disturbance. To eliminate external magnetic disturbance due to the air gap, it is desirable to construct the choke so that the air gap is entirely enclosed by the iron path as shown in Figure 2A.

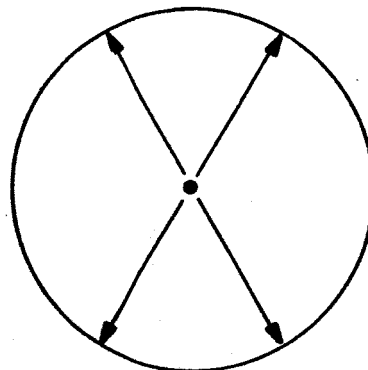
Since the air gap is entirely surrounded by iron, the gap will not cause external magnetic disturbance. However, the magnetomotive drops across the surface of the iron can cause external magnetic disturbance. Flux paths along the top and bottom of this cylindrical choke are shown on Figure 2B and 2C.

Calculations of the external magnetic field disturbance caused by these magnetomotive drops across the choke surface are shown in Appendix A. These calculations indicated that the maximum external magnetic field disturbance at a distance of 18 inches from the axis of a single section choke coil will be 1.32 gamma or 66 percent of the specification maximum. It is possible that this flux could add to the fields from other components to produce a larger total disturbance. Additional calculations in Appendix A indicate that the maximum magnetic field disturbance due to the choke

2A

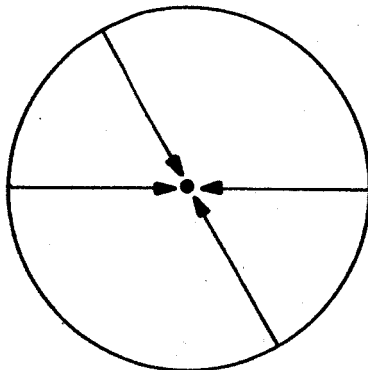


2B



TOP

2C



BOTTOM

2D

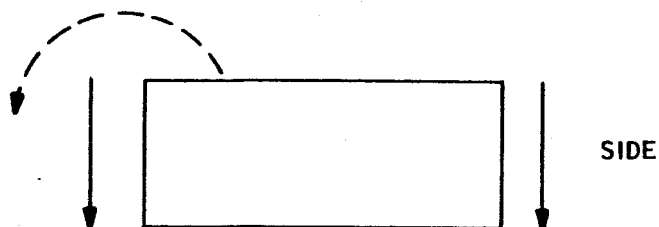


Figure 2 - CHOKE COIL FLUX PATHS



coil can be diminished to 0.082 gamma or 4.1 percent of the specification maximum by dividing the choke into two sections oriented with like poles back to back so that the external fields cancel (see Figure 7 in Appendix A). This latter approach will be used in the fabrication of a choke coil for this device.

E. VOLTAGE REGULATOR IMPROVEMENTS

Means of improving the regulator switching characteristics are currently being investigated to improve efficiency, allow an increase in the operating frequency, and improve the temperature stability. The circuit under investigation is shown on Figure 3. This circuit is similar to the regulator used previously^(*) except that transistor Q_3 and diode CR3 have been added to the circuit. Transistor Q_3 provides a snapacting switch that can be used to back-bias transistors Q_1 and Q_2 more rapidly through the lower impedance provided when Q_3 is suddenly switched ON. Transistor Q_3 is operated by the bias voltage across resistor R_2 and CR3. If transistor Q_4 is OFF, the voltage drop across CR3 will be zero, and current flow through R_2 to the base of Q_3 will render Q_3 conductive and back-bias current will flow through R_1 , Q_3 collector emitter junction to back-bias Q_2 and Q_1 .

Because the impedance of R_1 is low, a high back-bias current can be supplied to rapidly sweep the carriers out of the base region and provide more rapid turn off of Q_2 and Q_1 . This higher available back-bias current should improve the temperature stability of the germanium transistors, Q_2 and Q_1 , which provide the highest efficiency in this circuit. When Q_4 conducts, the current flow through CR4 pulls down the base voltage of Q_3 below its emitter potential shutting it off. This shutoff then blocks the flow of back-bias current, causing

(*) Lingle, J. T. Low Input Voltage DC to DC Converter, Final Report, 26 March 1964, pp. 12-15, Honeywell Inc. for National Aeronautics and Space Administration, Goddard Space Flight Center, Contract NAS 5-3441.



Fig. 1



nearly all of the current flowing through R_4 to flow through the emitter-base junction of Q_2 . Thus, most of the Q_4 current is effective in driving Q_2 . This is an improvement over the previous circuit because the current limiting function of Q_3 was accomplished by a resistor that would limit the amount of available back-bias current during TURN OFF. Also, during conduction of Q_4 , the back-bias circuit would allow current flow through the resistors R_1 , R_4 , and Q_4 . This current would detract from the available drive for Q_2 , consuming more power in the resistors and reducing the total circuit gain. Thus, this new circuit modification should accomplish the following:

- 1) Reduce regulator control circuitry losses.
- 2) Provide more back bias current for faster turn "OFF" and better high temperature performance.
- 3) Increase the circuit gain and turn on switching speed because Q_2 can be operated at higher gain and Q_4 can operate at a lower collector current.
- 4) Operation of the regulator at a higher frequency to reduce the filter size and weight (L_1 and C_2).

Preliminary breadboard experiments have indicated satisfactory operation. Further testing will be necessary to evaluate the benefits that can be obtained in switching speed, efficiency, and temperature stabilization.

The efficiency of the regulator section has been improved through the incorporation of a current drive transformer (T_2 in Figure 3) to supply drive power for the pulse width modulator chopping transistor (Q_1). The drive power is, therefore, proportional to load current, resulting in optimum drive over the load range and affording an improvement over the winding on the voltage transformer (T_1) previously used as the drive supply.



The previous voltage drive circuit had to be designed for worst-case conditions (maximum load, minimum input voltage). When the converter was operated at higher input voltage conditions and/or lighter load, the excess power provided by the drive supply was dissipated in a series resistor. The current drive supply does not require the incorporation of this series-dropping resistor, as the power supplied is approximately equal to that required at all times. The incorporation of the current drive resulted in a two to five percent increase in converter efficiency over the load and input voltage range. The current drive also enhances the reliability of the regulator circuit because transistor Q_1 will be less likely to run out of drive during overload.

Additional modifications, involving a reduction of the number of parts, were made in the regulator section. The emitter-follower buffer stage, following the unijunction ramp generator, and many of the diodes previously used for protection of various transistor emitter-base junctions have been eliminated. The buffer stage indicated was originally included to increase the input impedance to the differential amplifier and to provide increased ramp linearity. Operational tests over the temperature range -65°F to $+160^{\circ}\text{F}$ indicated that this buffer stage was unnecessary as the modified circuit operated with no degradation in performance. The protective diodes eliminated were also found to be unnecessary in the finalized regulator circuits. The reduction in the number of parts will obviously facilitate assembly, increase reliability, and reduce costs.

1. Computer Programming

A stress analysis will be made on all components in the voltage regulator. Drive current equations for the voltage regulator circuit will be programmed on a computer to obtain the optimum values and tolerance limits of circuit components. The normal and maximum power dissipation, as well as the current flow through each component, will be obtained. This information will be used to assure that each component is operated safely within its



rating and that the circuit will function properly under all input voltage, load, and temperature environments. The data on current flow through each component will be used in laying out the regulator package to ensure that the total current flow through the regulator will result in minimum external magnetic field disturbance.

F. POWER OSCILLATOR OPERATING FREQUENCY STUDIES

The low input voltage converters previously fabricated at Honeywell Ordnance have been designed to have a power oscillator operating frequency of approximately 700 cps or lower to achieve high converter efficiencies. This range of operating frequencies was chosen so that the switching and related switching losses per unit time would be minimized. The size and weight of the converter can be significantly decreased if the power oscillator section is operated at a higher frequency. The increased operating frequency decreases the necessary maximum flux in the power transformer core and makes it possible to realize a reduction in its size and weight. (The physical size of the feedback transformer and the switching reactor could, therefore, also be reduced).

The required flux in the core is inversely proportional to the frequency so that doubling the operating frequency while maintaining a specific input voltage reduces the maximum required amount of magnetic flux to one half of that previously needed. For the same maximum flux density, therefore, the transformer core cross-section area can be reduced to one half of the size previously required. A related reduction in core weight can be realized as the cross-sectional area is reduced. For example, the cross-sectional area of toroidal cores is the difference between the outside and inside radii, multiplied by the core length. Therefore, if the core area were reduced by fifty percent by halving the length, the total core weight would also be halved. Correspondingly, the copper length (weight) of each complete turn would be decreased by twice the reduction in core length.



If the core area is reduced by decreasing the outside diameter, the core weight decrease will be a function of the square of the decrease in outside radius. Consideration of transformer efficiency and limiting requirements on physical dimensions will determine the actual reduction in transformer weight realized with an increased operating frequency.

The weight of the power transformer can be reduced by operating the power oscillator at a higher frequency (approximately 1000 to 2500 cps) without appreciably decreasing the transformer efficiency. The core loss per pound at a specific flux density increases with operating frequency. However, for a specified flux-density-frequency product over certain frequency ranges (for example 400 cps to 2000 cps), the total core loss may not appreciably change as the weight of the core is correspondingly decreased with operating frequency. The transformer copper loss will of course decrease if the length of each turn is decreased. This decrease will usually compensate for slight increases in core loss when increasing the operating frequency from 400 cps to 2000 cps.

The switching losses presently appear to be the primary limiting factor to maintaining converter efficiency while increasing the operating frequency. These losses become more appreciable as the frequency increases because the power oscillator transistors then spend a larger percentage of the time in the high loss switching mode. The switching time (loss) per cycle must therefore be reduced to a minimum if efficient operation is to be realized, as the number of these cycles per second is increased.

The desirability of realizing efficient operation at reduced size and weight becomes even greater when considering converter applications in space vehicles. Therefore, considerable investigation is being conducted to increase the switching speed of the power transistors so that high converter efficiencies can be realized and maintained at reduced size and weight.



1. Two Feedback Transformer Method

A modification in the power oscillator circuit incorporating two feedback transformers (replacing the single transformer previously used) was investigated in an effort to realize higher transistor reverse bias voltages for faster switching of the power transistors (Figure 4). The power transistors utilized are constructed with a relatively large base region to provide the very low saturation resistances necessary for efficient operation of the converter. Although this wide base construction is necessary to meet the saturation requirements, it results in the transistors having an inherently long storage time (rated 15 microseconds typical), resulting in a slow turn off. This turn off time can be reduced, however, by forcing the transistor off with a high reverse bias or by forcing current through the base emitter junction in the reverse direction, thus removing the stored charge faster.

The reverse bias transistor voltages realized in a single feedback transformer circuit are clamped to the value of the forward emitter-base voltage of the transistor conducting on that particular half cycle. The circuit indicated in Figure 4 was designed so that the transformers (T_2 and T_3) would be momentarily decoupled during the switching interval such that higher reverse bias voltages would be applied to the transistor trying to turn OFF. This decoupling is realized through reactors L_A and L_B . Following the operation of the circuit through a half cycle, one first assumes transistor Q_1 conducting. During this time, winding N_{3A} on T_2 is serving as a source of reset power to the T_3 core through N_{3B} , L_B , and L_A . Just prior to the end of the half cycle, L_1 saturates, allowing the voltage developed across N_3 on T_1 to be applied to the common connection of L_A , L_B and that of N_{3A} and N_{3B} . This voltage pulse immediately appears across the N_{3A} winding, turning off Q_1 as L_A is saturated, affording only the resistive impedance of its windings. The application of this voltage pulse to N_{3B} is momentarily delayed, however, by L_B as it has been previously saturated in the opposite direction such as to oppose the current flow generated by the N_3 voltage pulse. The turn ON of Q_2 is thereby momentarily

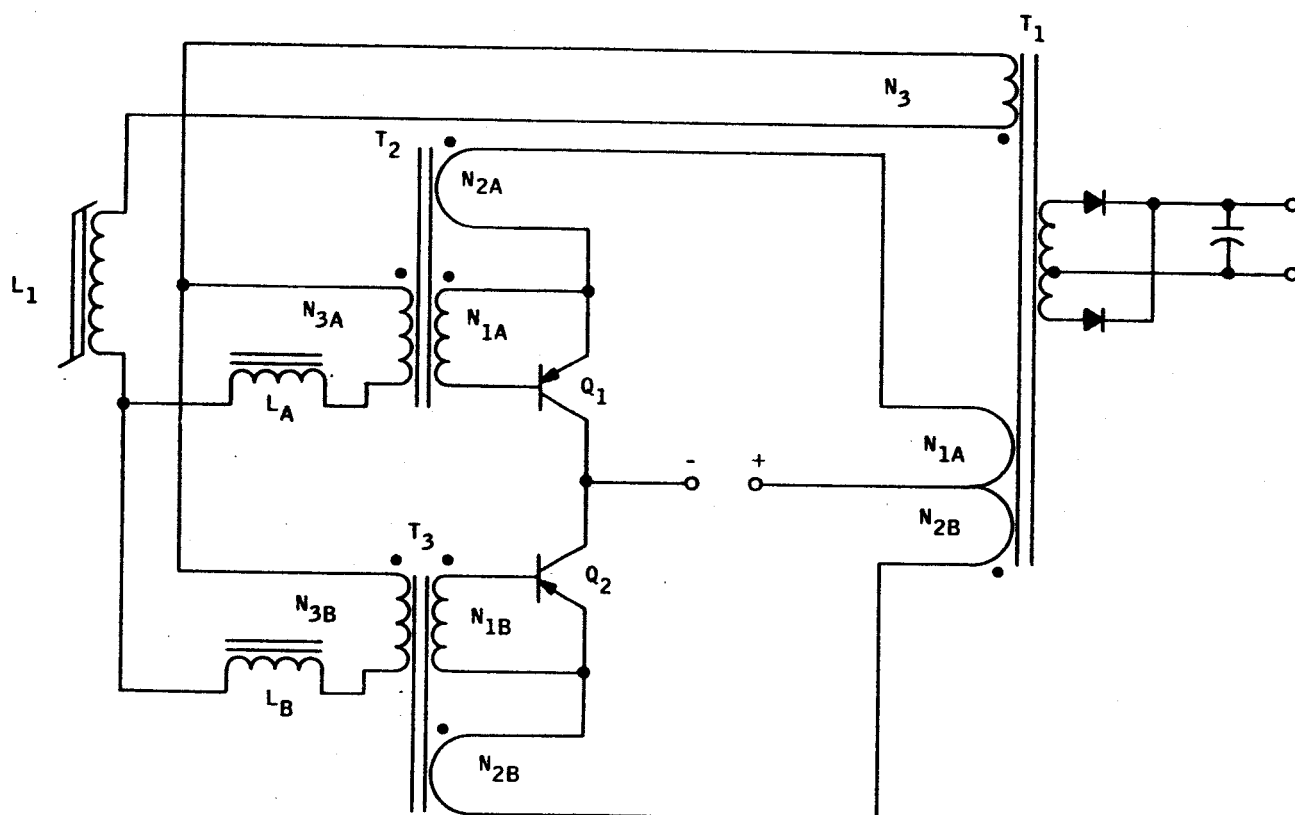


Figure 4 - EXPERIMENTAL TWO FEEDBACK
TRANSFORMER POWER OSCILLATOR CIRCUIT

delayed and the decoupling of T_2 and T_3 is realized. This results in a higher turn OFF voltage applied to the Q_1 base-emitter junctions. The succeeding half cycle sees T_2 being reset by N_{3B} and the corresponding action realized for that half cycle.

A limiting characteristic of the circuit described is that reactors L_A and L_B subtract from the reset power provided such that the T_2 and T_3 cores may move up the B-H curve until they are operating on one end of the curve. This results in high magnetizing currents and the loss of operating frequency control through the switching reactor L_1 . Because of this loss, the reactors L_A and L_B were designed for minimum inductance (while having a sufficient number of turns to realize saturation), and an air gap was introduced in T_2 , T_3 cores to provide some inherent reset.

The performance of this circuit indicated that very fast (less than 10 microseconds) transistor switching could be realized when the inductors L_A and L_B and the transformer cores (T_3 , T_4) were optimized. The problem encountered was that these optimum required values were not constant over the load range and wide input voltage range, characteristically a requirement of low input voltage converters. It followed, therefore, that for some conditions the inductors L_A and L_B subtracted from the transformer core reset so that the transformers were saturating; for other conditions, the decoupling provided by L_A and L_B was not sufficient to realize optimum switching. It was shown that the transformers were less susceptible to saturation when a larger air gap was introduced in the core. However, if this gap was made too large, the converter was much more difficult to start and tended to operate less efficiently during normal operations. Of specific difficulty in this analysis are the effects of stray inductances from various magnetic circuit components. Although this circuit concept can provide desirable operation, it is apparent that considerable investigation must be performed before it can be incorporated into a reliable system.

The power oscillator section will be an area of continued investigation during the next quarter.



SECTION V

CONCLUSIONS

The coaxial power oscillator and associated transformers have been designed. Emphasis has been placed on concentricity and symmetry to minimize external magnetic field disturbance. The converter has been designed so that it can be readily assembled and disassembled. Nearly all piece parts will be turned on a lathe and concentricity of the completed unit will be maintained to ± 0.003 inch. Fabrication of the coaxial converter model will begin shortly.

Calculations show that the external magnetic field disturbance 18 inches from a choke with a completely enclosed coil and air gap is 132 gamma, which is 66 percent of the maximum allowable 2 gamma disturbance. Although this is below the maximum specification limit, this disturbance could add to other component fields to cause a total disturbance greater than the limit. Additional calculations establish that a dual section choke with the respective sections oriented so that the external magnetic fields cancel will produce a much lower magnetic field disturbance of only 0.082 gamma, or about four percent of the limit. It can be concluded from these calculations that a practical choke coil can be fabricated to meet the magnetic field disturbance requirements. The dual section choke will lower considerably the external magnetic field disturbance.

Circuit investigations have established that the regulator ramp generator can be simplified without sacrificing regulator performance. Preliminary examination of the back-bias and drive circuitry for the pulse-width modulator has shown that the following changes enhance circuit performance.

- 1) Obtain the drive power for the chopping transistor (Q_1 , Figure 2) by means of a current transformer T_2 in series with the secondary windings N_2 on the output transformer T_1 .



- 2) Place a transistor Q_3 and a diode CR_3 in the back-bias circuit.

Item 1), above, provides regulator drive proportional to load current, optimizing the drive power over the load range and thus maintaining maximum efficiency throughout the load range. This circuit arrangement is particularly beneficial when the input voltage and load vary widely, as in the case for the converter under development here. With the previous circuit, voltage drive was obtained from T_1 , and it was necessary to provide sufficient drive for the worst-case condition. This resulted in excessive drive losses during other conditions. Breadboard experiments with the current drive in the regulator have shown improved performance.

Item 2) above provides a lower impedance path for the back-bias circuit so that the chopping transistors can be shut off more rapidly. This circuit also removes the back-bias current when the transistors are forward biased. This results in lower power dissipation and increases the regulator gain and switching speed. The higher available back-bias current improves the regulator temperature stability. These circuit changes will be incorporated in the model that will be fabricated shortly.

Methods of improving the power oscillator switching speed are currently being investigated. Basically, these involve decoupling the back-biased transistor from the feedback transformer so that the switching OFF transistor can be back-biased to a higher voltage. Preliminary investigation has shown that more rapid switching can be obtained. This work will be continued during the next quarter.

The non-magnetic components and materials requirement of this device has received special attention, and materials and components have been selected that meet these requirements.



Transistors present the greatest problem in meeting these requirements. Although the main oscillator transistors can be fabricated from non-magnetic materials, some of the intermediate power transistors use magnetic cases and leads. Some of these can be obtained with non-magnetic cases with a possible increase in cost. The majority of the small signal transistors can be obtained with non-magnetic cases.



SECTION VI

PROGRAM FOR THE NEXT QUARTER

During the next quarter, the coaxial power oscillator will be fabricated and tested. Initially, the oscillator will be tested with an existing breadboard regulator. A packaged regulator, which can be attached to the converter model, will also be fabricated. The packaged regulator will be designed for minimum external magnetic field disturbance and will be easily detachable from the coaxial converter so that these two sections can be checked separately for external magnetic field disturbance.

Parameter variation calculations will be programmed on the computer and will be completed during the next quarter.

Investigations will continue on methods for improving the switching speed of the power oscillator; the investigations will be directed toward the use of higher back-bias voltage on the oscillator transistors. Further, operation at higher frequencies will be studied to determine the optimum trade-off between size, weight, and efficiency for this application.

Before assembly into the unit, the secondary windings on the transformers will be excited with dc and checked for external magnetic field disturbance with the magnetometer to ensure that the windings have been uniformly spaced on the core to cancel external fields. The power oscillator and regulator will be checked individually with the magnetometer to verify that they cause no appreciable magnetic field disturbance. Toward the latter part of the next quarter, arrangements will be made at an outside facility to map the external magnetic field generated by the converter regulator.



SECTION VII

IDENTIFICATION OF PERSONNEL

H. T. MOOERS, Project Supervisor

Experience

Presently project supervisor in the Electro-Mechanical section of the Honeywell Ordnance Division with responsibility for electronic and influence fuzing and power supplies.

Other Honeywell experience as:

Staff Assistant, Semiconductor Sales (3 years). Responsibility for directing the market analysis group, the specifications group, and for coordinating the sales effort with the applications laboratory, the engineering department and the production department.

Assistant Director of Engineering, Semiconductor Division (1 year). Responsibility for staffing, hiring, organization and operation of the Boston Semiconductor engineering group.

Chief Application Engineer (2 years). Supervisor for the group charged with developing and publishing circuits and circuit design techniques.

Electrical Research Engineer for solid-state research group (4 years). Duties included creating and directing the complete support functions for the semiconductor research effort. Activity included the operation of a pilot line to evaluate processing techniques and designs.



Prior to joining Honeywell, manager of the Military Electronics Department of Rosemount Engineering Company. Responsible for growth and profitable operation of the group, including all phases of product planning, development fabrication, testing, and merchandizing.

Two years as Manager of Engineering for American Monarch Company. Supervised development and manufacturing support for relays, transformers, transistor inverters, regulated power supplies, resonant transformers, and other associated products.

Professional Background

BSE and MSEE, University of Minnesota

Thesis, "Low Frequency Noise in Type A Transistors"

Member: Tau Beta Pi-Honorary Engineering Fraternity

Eta Kappa Nu-Honorary Electrical Engineering Fraternity

Institute of Electrical and Electronic Engineers

Registered Professional Engineer in Minnesota



J. T. LINGLE, Project Engineer

Experience

Currently assigned in the design and development of solid-state low input voltage power converters, inverters voltage regulators, transistor circuitry, and electrical systems.

Specific examples of assignments and experience include:

Project engineer on low input voltage conversion programs, specializing in design and development of solid-state power supplies such as current feedback converters for photo-flash applications; three-phase power supply with regulated poly phase, ac constant current, and dc outputs; and inverters for space applications.

Experience dating back to 1952 on servo-systems, applications of transistors, power converters, switching circuits, voltage regulators, thermoelectric devices, and radio noise suppression.

Professional Background

BSEE, University of Minnesota

Registered Professional Engineer, State of Minnesota

Publications

"Low Input Voltage Conversion"

17th Annual Power Sources Conference, May 1963.

"Low Input Voltage Conversion - II"

18th Annual Power Sources Conference, May 1964.



Military Contract Experience

<u>Project</u>	<u>Contract No.</u>	<u>Position</u>
LOW INPUT VOLTAGE CONVERSION		
Investigation of all known methods of low input voltage power conversion, determination of the optimum approach to convert the low input voltage of fuel cells, thermionic and thermo-electric generators, solar cells, and single cell batteries to higher more usable voltages; and design, develop and fabricate two 50 watt and two 150 watt converter models.	DA-36-039-SC-90808 Signal Corps	Project Engineer
LOW INPUT VOLTAGE DC TO DC CONVERTER		
Design, development, and fabrication of a highly efficient regulated transistor converter to convert the output of fuel cells thermo-electric generators, thermionic generators, solar cells, and other single cell sources to 28.0 volts dc. The converter requirements are: input voltage range 0.8 to 1.6 volts. Output voltage regulation: 28 volts $\pm 1\%$ over input voltage, temperature, and load range. Efficiency: over 70%	NAS 5-3441 NASA Goddard	Project Engineer



<u>Project</u>	<u>Contract No.</u>	<u>Position</u>
LOW VOLTAGE CONVERTER Design, develop, and fabricate six low voltage converter models, for operation from thermionic diode sources. Three models are designed to operate from a 0.6 to 0.8 volt source, three models are designed to operate from a 3.0 to 4.0 volt source. Output power from 90 watts to 160 watts at 50 volts.	#95635 J. P. L.	Consultant Engineer
1200 WATT THERMOELECTRIC AUXILIARY POWER SUPPLY FOR SURFACE LAUNCHED MISSILES A feasibility study contract investigating the possibility of converting waste heat from a missile combustion chamber directly into electric energy by utilizing intermetallic thermoelectric elements. Also includes the design of dc to dc and dc to three phase ac regulated transistor inverters.	NOw-60-0031	Project Engineer
POWER TRANSISTOR CIRCUITRY STUDY Study of the Signal Corps Engineering Laboratory Oscillator Circuit relating the effects of circuit parameters and transformer construction to the switching characteristics and optimization of those parameters for maximum performance.	DA-36-039-SC-71161 DA Project No. 3-99-09-022 Signal Corps Project No. 162B	Dev. Engr.



<u>Project</u>	<u>Contract No.</u>	<u>Position</u>
G2389 GEMINI INVERTER		
Design of input line switching voltage regulator and filter for dc to 400 cps, sine wave, 50 volt. inverter for Gemini Spacecraft.	P. O. ICDQ 0791 Honeywell Aero-nautical Division	Sen. Dev. Engr.
SCOUT INVERTER		
DC to precision 400 cps sine wave regulated inverter for the Blue Scout missile	P. O. ICDQ-0078 Honeywell Aero-nautical Division	Sen. Dev. Engr.
XG2369 - ACCA CONTROL ANALYZER POWER SUPPLY		
400 cycle precision power supply with several highly regulated three phase ac and dc outputs for aircraft preflight automatic checkout system. Degree of regulation on order of $\pm 0.1\%$ under all environmental load and input voltage variations.	NOas 60-147B Navy	Sen. Dev. Engr.



K. J. JENSON, Development Engineer

Experience

Presently assigned in the design and development of solid-state low input voltage power converters, inverters, voltage regulators, and transistor circuitry.

Other Honeywell experience:

Design and development of solid-state power supplies.

Design and development of underground telemetry system utilizing properties of magnetic fields for signal transmission.

Design and development of test equipment for FMU-30/B Land Mine Fuze.

Pre-shipment and flight testing the FMU-30/B Fuze.

Analysis of semiconductor switching applications as related to the Sergeant Warhead.

Qualification testing of nuclear adaption kit sub-assemblies.

Professional Background

BSEE, University of Wisconsin

Completing MSEE, University of Minnesota

Member: Tau Beta Pi Honorary Engineering Fraternity



APPENDIX A

CALCULATION OF THE EXTERNAL MAGNETIC FIELD DISTURBANCE AROUND A CHOKE COIL WITH A TOTALLY ENCLOSED COIL AND AIR GAP.



CALCULATION OF THE EXTERNAL MAGNETIC FIELD DISTURBANCE AROUND A CHOKE COIL WITH A TOTALLY ENCLOSED COIL AND AIR GAP

The choke coil configurations shown on Figures 2 and 7 minimize the external magnetic field disturbance because both the air gap and the coil are totally enclosed by a high-permeability "mu-metal" magnetic enclosure. The magnetomotive drop along the choke coil outer surface produces a small magnetic gradient, exciting an external magnetic field. The calculations below establish:

- 1) The strength of the choke coil external magnetic moment.
- 2) The external magnetic field disturbance at three positions 18 inches away from a single-section choke coil.
- 3) The external magnetic field disturbance at three positions 18 inches away from a dual-section choke coil arranged back to back with poles bucking.

Calculations on the above follow:

1) Calculation of the Strength of the Choke Coil External Magnetic Moment

The flux flow through the magnetic material produces a magnetomotive drop along the surface in the direction of flux flow (see Figure 5). This magnetic gradient will be small due to the high permeability core material; however, this gradient will produce an external magnetic field. The external magnetic field disturbance can be calculated by determining the magnetic moment of the equivalent magnetic dipole and then using the inverse cube law to calculate the external field at various points in space.

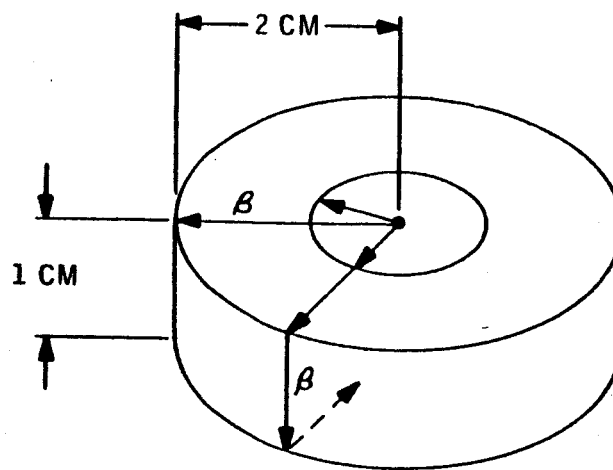


Figure 5 - CHOKER COIL EXTERNAL MAGNETIC MOMENT



The external magnetic moment of the choke coil can be calculated as follows:

- Given:
- (1) Choke dimensions of 1 cm high and 4 cm diameter. Permeability of the "mu-metal" diminishes as the flux density increases.
 - (2) Assume an operating flux density of 5,300 gauss where $\mu = 21,000$.
 - (3) Assume a uniform cross sectional area throughout the choke to maintain constant flux density throughout.

If the choke coil magnetic path is constructed with a uniform cross-sectional area, the flux density will be uniform and the magnetomotive drop per centimeter can be assumed constant.

The choke coil will then appear to be a short round magnet as shown in Figure 5. The flux will travel from the center toward the upper circular surface, radially outward toward the edge, down the cylindrical surface to the bottom circular surface, inward toward the center, and then up through the center to complete the path.

The equivalent magnetic circuit of the choke coil is shown on Figure 6. The circuit consists of a magnetomotive force, $F = \oint \vec{H} \cdot d\vec{l}$, which forces flux through the reluctance of the air gap, R_A , the internal iron R_{II} , and the iron path which borders the choke external surface R_{IE} . Because the air gap and coil is completely surrounded by the mu-metal shell, the "mu-metal," in effect, places a shunt (R_{IE}) across the magnetomotive source.

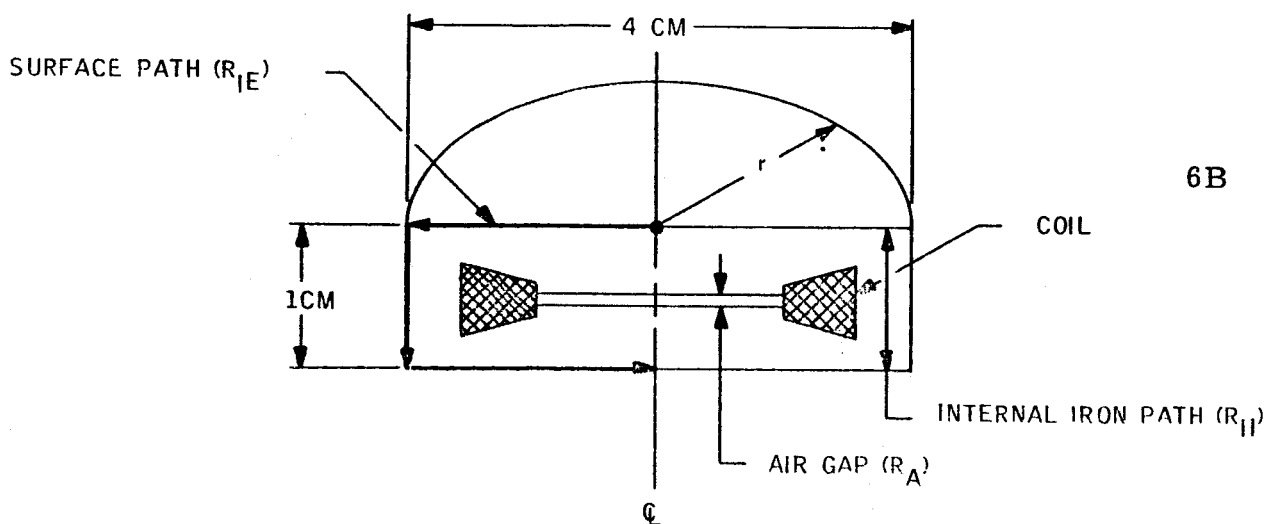
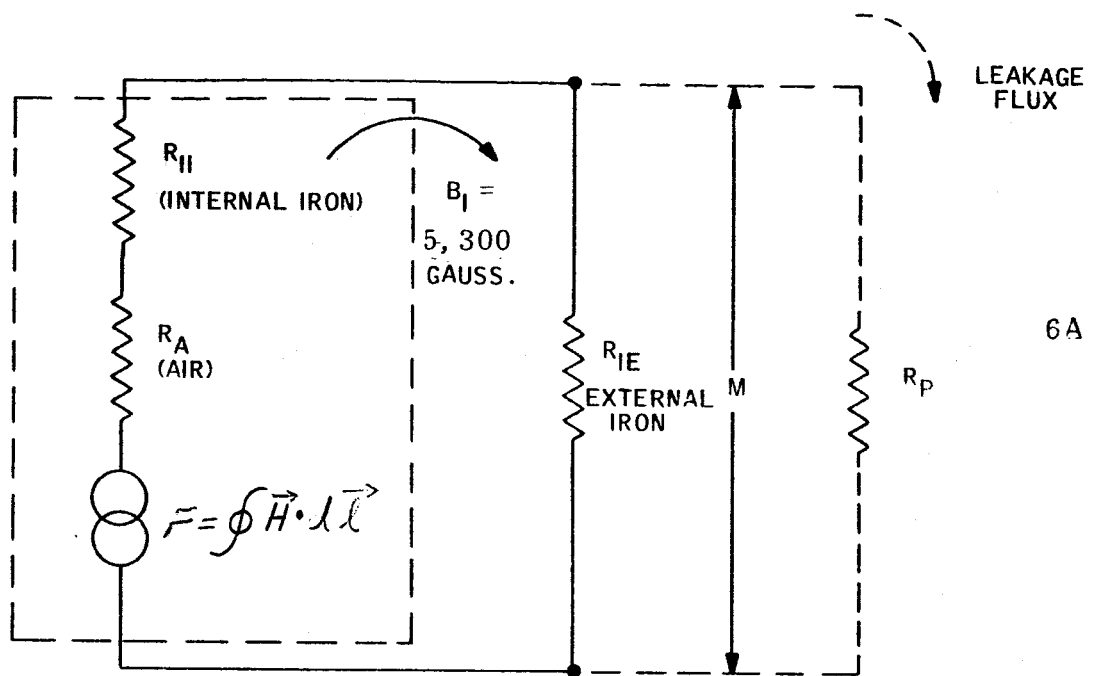


Figure 6 - EQUIVALENT MAGNETIC CIRCUIT



As far as the external leakage flux is concerned, the magnetic moment, M , is clamped to a low value by the low reluctance of the mu-metal case (R_{IE}). The magnetomotive force which is available to drive flux through an external leakage path (R_p) at some point, p , in space is determined by the flux reluctance drop across the external iron (R_{IE}).

If the air gap does not exist, the magnetizing force, H , required to operate the "mu-metal" at 5,300 gauss is:

$$\begin{aligned} H &= \frac{B_{\text{iron}}}{\mu_{\text{iron}}} \\ &= \frac{5,300 \text{ gauss}}{21,000} \\ &= 0.252 \text{ oersted} \\ &= 0.252 \frac{\text{gilbert}}{\text{cm}} \end{aligned}$$

The total magnetomotive force would be equal to the H field multiplied by the mean path length through the iron. The assumption is made here that the outer surface flux density will be limited to 5,300 gauss. The worst case (maximum magnetic moment) will exist for the longest mean path length. For this condition the maximum path length at the choke outer surface will be assumed because this is the worst case and also because the flux is assumed to be 5,300 gauss at this surface. The flux path length across the outer surface (R_{IE}) is 5 centimeters. The total path length ($R_{IE} + R_A + R_{II}$) is six centimeters, counting the return path through the center of the coil. The equivalent circuit on Figure 6A shows that the internal path is not effective in producing the external leakage flux and hence the effective path length is taken as 5 cm. Because the required field is 0.252 gilbert/cm, the required magnetomotive force is:

$$\begin{aligned} \text{MMF} &= 0.252 \frac{\text{gilberts}}{\text{cm}} (5 \text{ cm}) & (1) \\ &= 1.26 \text{ gilberts} \\ &= 1.26 \text{ gilberts} (0.796 \frac{\text{ampere turns}}{\text{gilbert}}) \\ &= 1.00 \text{ ampere turns} \end{aligned}$$



The coil magnetic moment is defined as:

$$M = NIA, = MMF \times A \quad (2)$$

where: M = magnetic moment

N = number of turns

I = current

A = area of coil.

Since the internal coil in this case divides the choke coil iron into two equal coaxial areas, it can be assumed that the mean area of the coil is equal to one half the total area of the choke circular surface. Therefore:

$$A = \frac{\pi r^2}{2} = \frac{\pi (2)^2}{2}$$

$$A = 2\pi,$$

and it was previously determined that $NI = 1.00$ ampere turn.

Therefore, the magnetic moment is:

$$M = 1.00 \text{ ampere turn } (2\pi \text{ cm}^2)$$

$$= 1.00 (2\pi) \text{ ampere (cm)}^2$$

$$M = (2\pi) \times 10^{-4} \text{ ampere (meters)}^2$$

This is then the magnetic moment of the coil which drives a flux of 5,300 gauss through the outer surface of the choke coil iron. As far as the external leakage flux is concerned, it will be induced by a magnetic dipole having this moment. The reluctance of the internal air gap and the H field required to drive flux through it do not enter into the external magnetic moment because this additional magnetizing force is only used in driving the high density flux through the internal



air gap. The external magnetic field can be calculated from the magnetic moment of this coil, neglecting the "mu-metal" choke. The value of the magnetic moment computed above is conservative (slightly larger than the actual value) because worst case assumptions were made for the flux mean path length.

2) Calculation of the External Magnetic Field Disturbance Around A Choke Coil With Totally Enclosed Coil and Air Gap

The magnetic field intensity at various points in space away from the choke coil can be determined by the following formula: (*)

$$B = \frac{\mu_o}{4\pi} \left[\frac{3 M \cos \theta}{r^4} \vec{r} - \frac{1}{r^3} \vec{M} \right] \quad (3)$$

where: B = flux density in webers/m²

μ_o = Permeability of space = $4\pi \times 10^{-7}$ $\frac{\text{webers}}{\text{ampere meter}}$

\vec{M} = Magnetic moment vector of dipole
= $2.00\pi \times 10^{-4}$ ampere (meters)²

\vec{r} = Distance from the center of the dipole to the point

θ = Angle between \vec{M} and \vec{r}

For a distance 18 inches from the center of the choke coil $|\vec{r}| = 0.457$ meter.

Using this equation, the field intensity can be found at three points as follows:
(see Figure 7)

(*) Shortley and Williams, "Elements of Physics", Third edition, Prentice-Hall, 1961, p. 775.

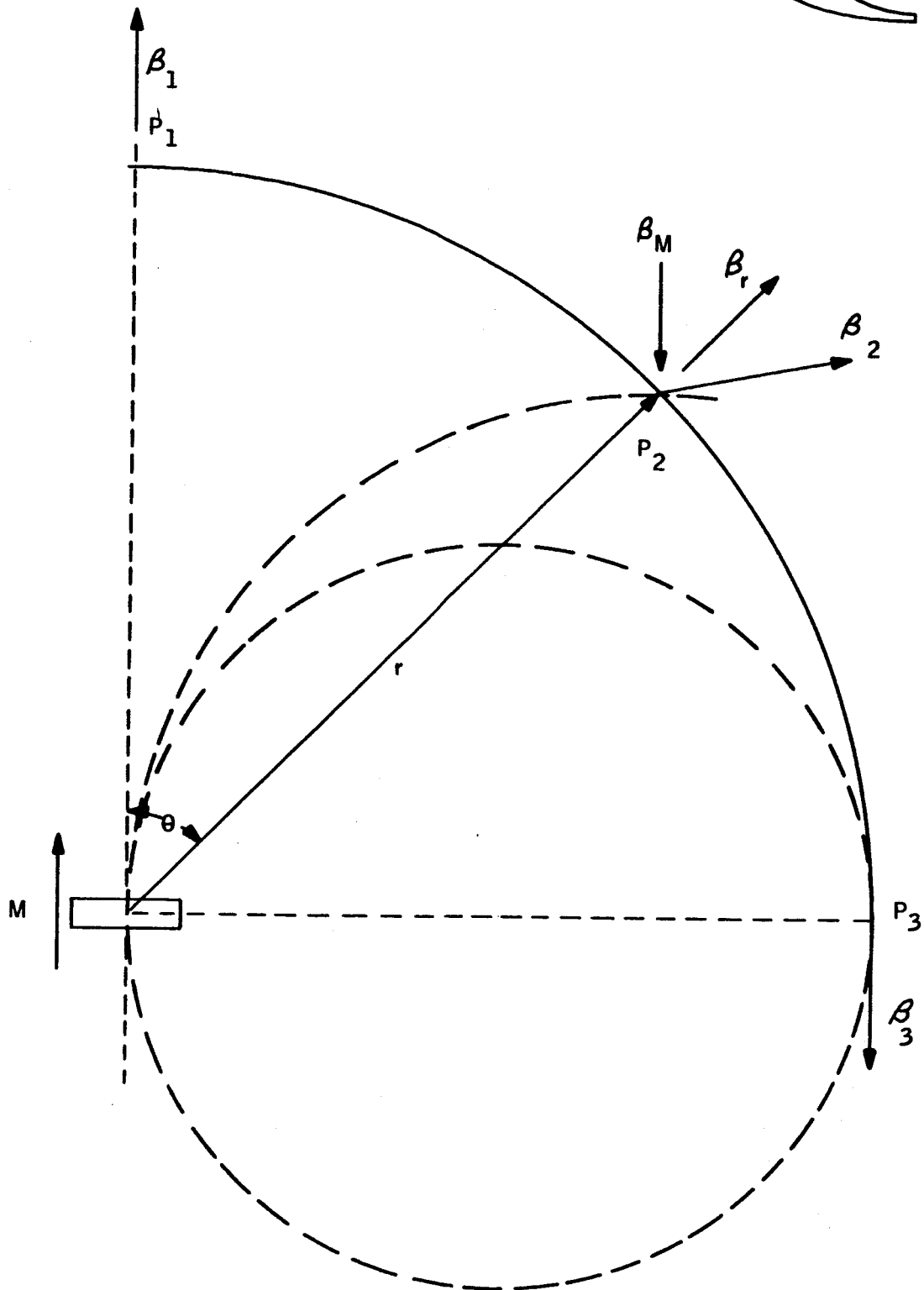


Figure 7 - CALCULATION OF THE MAGNETIC FIELD AROUND A SINGLE SECTION CHOKE COIL



Point I

For P_1 , $\theta = 0^\circ$

$$B_1 = \frac{4\pi \times 10^{-7}}{4\pi} \left[\frac{3(2.00 \pi \times 10^{-4}) \cos 0^\circ (0.457/0^\circ)}{(0.457)^4} - \frac{2.00 \pi \times 10^{-4} / 0^\circ}{(0.457)^3} \right]$$

$$B_1 = \frac{10^{-7} \cdot 2(2.00 \pi \times 10^{-4})}{(0.457)^3} = \frac{4.00 \pi \times 10^{-11}}{0.0958}$$

$$B_1 = 13.2 \times 10^{-10} \text{ webers/meter}^2$$

$$= 13.2 \times 10^{-6} \text{ gauss}$$

$$B_1 = 1.32 \text{ gamma}$$

Point II

For P_2 $\theta = 45^\circ$

substituting in equation (3) gives:

$$B_2 = \frac{4\pi \times 10^{-7}}{4\pi} \left[\frac{3(2\pi \times 10^{-4}) \cos 45^\circ}{(0.457)^4} (0.457 / 45^\circ) - \frac{2\pi \times 10^{-4} / 0^\circ}{(0.457)^3} \right]$$

$$B_2 = \frac{10^{-11} [13.42 / 45^\circ - 6.32 / 0^\circ]}{0.0958}$$

$$B_2 = \frac{10^{-11} [13.42 (0.707) / 0^\circ + 13.42 (0.707) / 90^\circ - 6.32 / 0^\circ]}{0.958 \times 10^{-1}}$$

$$B_2 = \frac{10^{-10} [9.48 / 0^\circ + 9.48 / 90^\circ - 6.32 / 0^\circ]}{0.958}$$



$$B_2 = \frac{10^{-10} [3.16 \angle 0^\circ + 9.48 \angle 90^\circ]}{0.958}$$

$$B_2 = [3.30 \angle 0^\circ + 9.88 \angle 90^\circ] \times 10^{-10}$$

$$\tan \alpha = \frac{3.30}{9.88} = 0.333$$

$$\alpha = 18.42^\circ, \cos \alpha = 0.944$$

$$B_2 = \frac{9.88 \times 10^{-10}}{\cos \alpha} = 10.48 \times 10^{-10} \text{ at } 18.40^\circ \text{ from the horizontal}$$

$$90^\circ - \alpha = 71.58^\circ$$

$$B_2 = 10.48 \times 10^{-10} \text{ weber/(meter)}^2$$

$$= 10.48 \times 10^{-6} \text{ gauss}$$

$$= 1.048 \text{ gamma with flux flow oriented at an angle of } 71.58^\circ \text{ from the polar axis.}$$

Point III

$$\text{For } P_3, \theta = 90^\circ$$

Substituting in equation (3) gives:

$$B_3 = \frac{4\pi \times 10^{-7}}{4\pi} \left[\frac{3(2\pi \times 10^{-4}) \cos 90^\circ (0.457 \angle 90^\circ)}{(0.457)^4} - \frac{2\pi \times 10^{-4} \angle 0^\circ}{(0.457)^3} \right]$$

$$\cos 90^\circ = 0$$

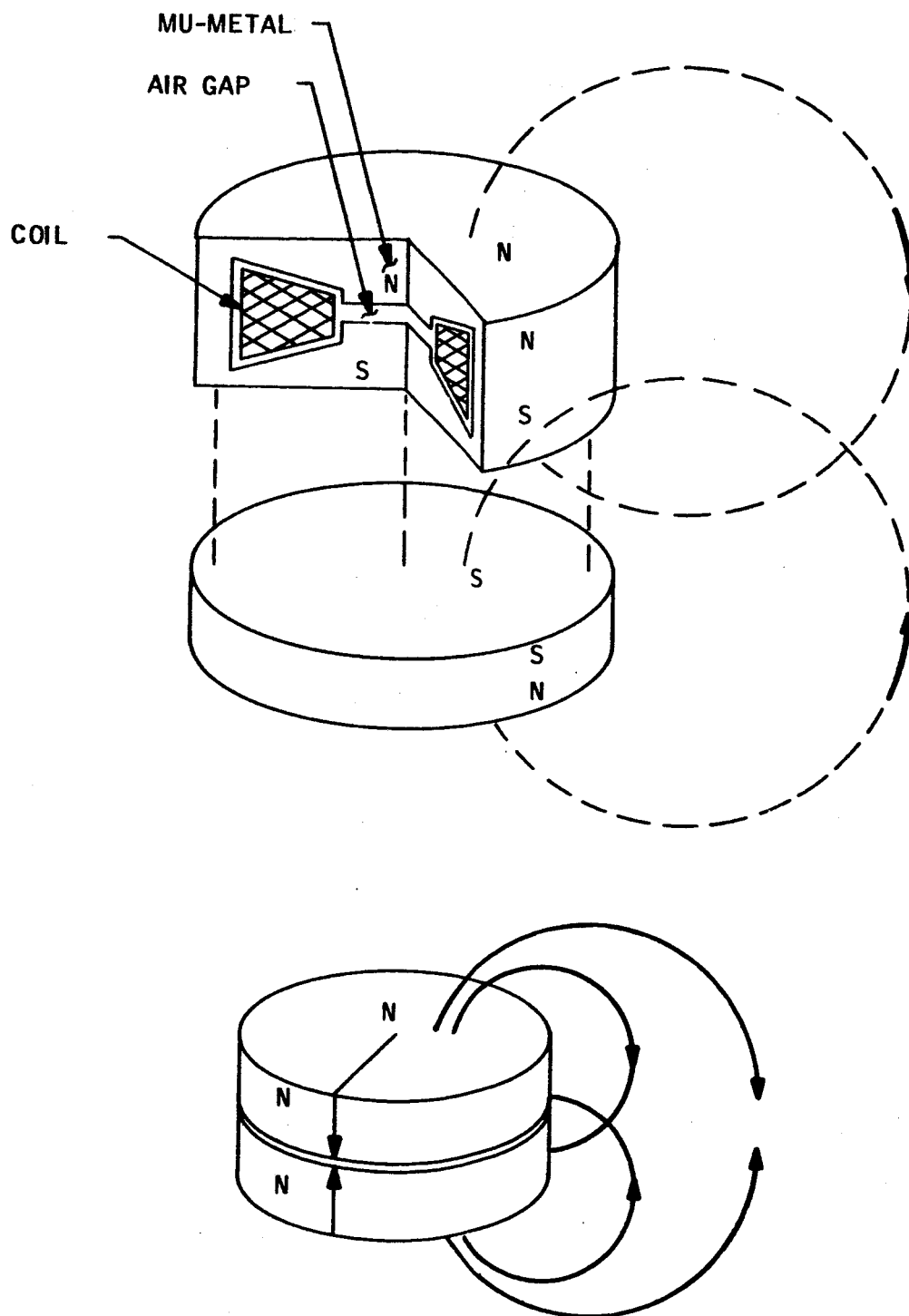


Figure 8 - DUAL SECTION CHOKE COIL ORIENTED WITH EXTERNAL FIELDS
BUCKING



$$B_3 = 10^{-7} \left[- \frac{2\pi \times 10^{-4} / 0^\circ}{0.958 \times 10^{-1}} \right]$$

$$B_3 = -6.6 \times 10^{-10} / 0^\circ ; \text{ or } 6.6 \times 10^{-10} / 180^\circ$$

$$= -6.6 \times 10^{-10} \text{ weber}/(\text{meter})^2$$

$$= -6.6 \times 10^{-6} \text{ gauss}$$

$$= -0.66 \text{ gamma parallel to the polar axis.}$$

3) Calculation of the External Magnetic Field Disturbance Around a Dual Section Choke Coil Oriented with External Fields Bucking

It is apparent that the magnetic disturbance of this choke coil section is under the 2 gamma specification requirement. However, it is possible that the magnetic moment of this device could add to the magnetic moment of another component to produce a total field disturbance greater than the allowable maximum.

To reduce further the magnetic field disturbance, it is possible to construct the choke coil in two sections and orient the sections so that their respective external leakage fields cancel. This is shown on Figure 8. Like repelling poles are butted against each other.

To estimate the external magnetic field disturbance, we shall assume that each magnetic dipole produces an external magnetic field independent of the other. This assumption may not be strictly valid, however, because the permeability of the other choke in close proximity may distort the field and perhaps diminish the total external magnetic field disturbance. The assumption that the two dipoles act independently should provide a satisfactory estimate.



Figure 9 shows the geometrical construction of the dual section choke in space. Each choke is assumed to possess the same magnitude of magnetic dipole but the polarity of one is south (or negative). The external magnetic field disturbance will be determined by the differences in the magnitudes of the radii r_1 and r_2 and the angle θ between the axis and the respective radius.

(I) Calculate the external magnetic flux disturbance at point P_b which is 18 inches from the geometric center of the two chokes and a line drawn between the geometric center and point P_b is displaced 45° from the choke axis.

Given: $M_{L1} = -2\pi \times 10^{-4}$ ampere (meter)²

$$M_{L2} = +2\pi \times 10^{-4} \text{ ampere (meter)}^2$$

$$\begin{aligned} r_o &= 18 \text{ inches} \\ &= 0.457 \text{ meter} \end{aligned}$$

$$\theta_o = 45^\circ$$

$$\begin{aligned} D &= \text{distance between center of } L_1 \text{ and } L_2 \\ &= 0.01 \text{ meter} \end{aligned}$$

$$\theta_1 = \text{angle between } r_1 \text{ and axis}$$

$$\theta_2 = \text{angle between } r_2 \text{ and axis}$$

By dropping a perpendicular from the geometric center of the dual choke assembly to r_1 , it can be seen that r_1 is approximately $\frac{0.01 \times 0.707}{2}$ or 0.00353 meter longer than r_o . Similarly, r_2 is 0.00353 meter shorter than r_o .

$$\text{Thus } r_1 = 0.4605 \text{ meter}$$

$$r_2 = 0.4535 \text{ meter}$$

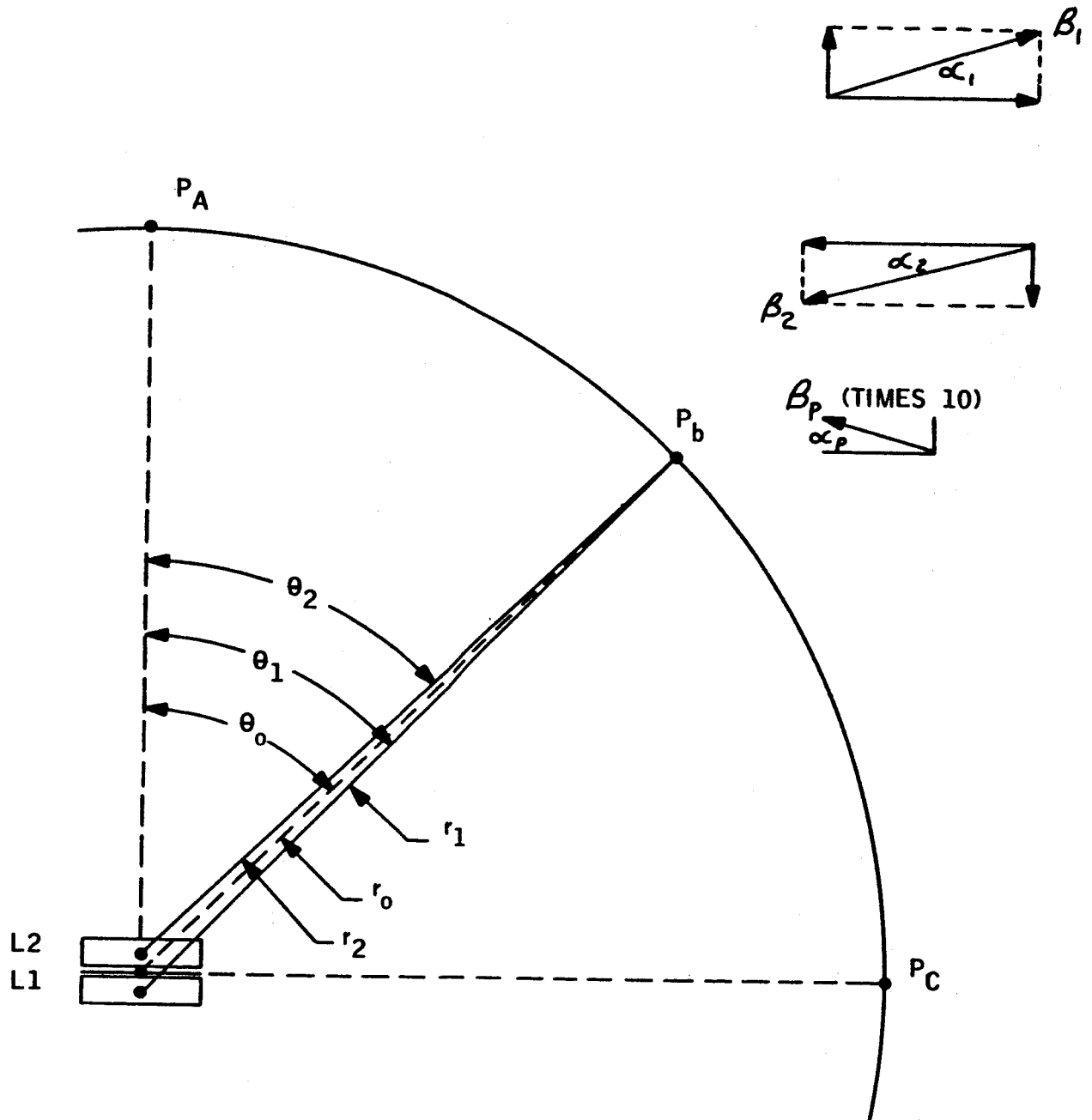


Figure 9 - GEOMETRICAL CONSTRUCTION FOR CALCULATION OF THE EXTERNAL MAGNETIC FIELD OF A DUAL SECTION CHOKE



The distance from P to the axis is 0.707×0.457 or 0.323 meter. The angle between the axis and r_1 and r_2 is:

$$\sin \theta = \frac{0.323 \text{ meter}}{r_1} = \frac{0.323}{0.4605}$$

$$= 0.702$$

$$\theta_1 = 44.6^\circ$$

$$\sin \theta_2 = \frac{0.323 \text{ meter}}{r_2} = \frac{0.323}{0.4535}$$

$$= 0.713$$

$$\theta_2 = 45.5^\circ$$

Substituting these values in equation (3) gives:

$$B_{1b} = \frac{4\pi \times 10^{-7}}{4\pi} \left[\frac{3 (\pi \times 10^{-4}) \cos 44.6^\circ (0.4605) / 44.6^\circ}{(0.4605)^4} - \frac{2\pi \times 10^{-4} / 0^\circ}{(0.4605)^3} \right]$$

$$B_{1b} = \frac{10^{-11} \times 2\pi}{0.098} [3 \times 0.712 / 44.6^\circ - 1.0 / 0^\circ]$$

$$B_{1b} = 6.444 \times 10^{-10} [2.136 (\cos 44.6^\circ + j \sin 44.6^\circ) - 1.0]$$

$$= 6.444 \times 10^{-10} [1.52 - 1.0 + j 1.498]$$

$$B_{1b} = 6.444 \times 10^{-10} (0.52 + j 1.498)$$

$$\tan \alpha_1 = \frac{0.52}{1.498} = 0.347$$

$$\alpha_1 = 19.15^\circ$$



Substituting values for L_2 in equation (3) gives:

$$B_{2b} = \frac{4\pi \times 10^{-7}}{4\pi} \left[\frac{-3 (2\pi \times 10^{-4}) \cos /45.5^\circ (0.4535) /45.5^\circ}{(0.4535)^4} + \frac{2\pi \times 10^{-4} /0^\circ}{(0.4535)^3} \right]$$

$$B_{2b} = \frac{10^{-11} \times 2\pi}{0.093} [-3 \times 0.701 /45.5^\circ + 1.0 /0^\circ]$$

$$B_{2b} = 6.796 \times 10^{-10} [-2.101 (\cos 45.5 + j \sin 45.5^\circ) + 1.0]$$

$$= 6.796 \times 10^{-10} [-2.101 (0.701) - j 2.101 (0.713) + 1.0]$$

$$= 6.796 \times 10^{-10} [-1.473 - j 1.449 + 1.0]$$

$$B_{2b} = 6.796 \times 10^{-10} [0.473 - j 1.499]$$

$$\tan \alpha_2 = \frac{-0.473}{-1.499} = 0.3158$$

$$\alpha_2 = 17.5^\circ$$

$$B_{2b} = -3.214 - j 10.18$$

$$B_{1b} = +3.350 + j 9.66$$

$$B_{pb} = (0.136 - j .52) \times 10^{-10} \text{ webers/(meter)}^2$$

$$\tan \alpha_p = \frac{0.136}{0.52} = 0.2617$$

$$\alpha_p = 14.65^\circ$$

$$\cos 14.65^\circ = 0.968$$



$$B_{pb} = \frac{0.52}{0.968} \times 10^{-10}$$

$$B_{pb} = 0.5336 \times 10^{-10} \text{ weber/ (meter)}^2$$

$$B_{pb} = 0.5336 \times 10^{-6} \text{ gauss}$$

$$= 0.05336 \text{ gamma,}$$

$$\text{and this is } \frac{0.05336}{2.0} = 0.02166$$

or 2.166 percent of the specification requirement.

This it can be seen that splitting the choke coil into two opposing sections (as far as external leakage flux is concerned) results in a substantial reduction in external magnetic field disturbance at 18 inches.

(II) The field disturbance at PA can also be readily determined.

$$\text{At PA, } \theta_1 = \theta_2 = 0$$

$$r_1 = r_o + 0.005$$

$$= 0.457 + 0.005$$

$$= 0.462 \text{ meter}$$

$$r_2 = r_o - 0.005$$

$$= 0.457 - 0.005$$

$$= 0.452 \text{ meter}$$

Since $\theta = 0$, $\cos \theta = 1.0$



Then using equation (3) determine B_{1A} :

$$B_{1A} = \frac{4\pi \times 10^{-7}}{4\pi} \left[\frac{3(2\pi \times 10^{-4})(1)(4.62) \angle 0^\circ}{(0.462)^4} - \frac{2\pi \times 10^{-4} \angle 0^\circ}{(0.462)^3} \right]$$

$$B_{1A} = \frac{10^{-11} (2\pi)}{(0.462)^3} [(3 - 1)]$$

$$B_{1A} = 12.84 \times 10^{-10} \angle 0^\circ \text{ weber/ (meter)}^2$$

Next determine; B_{2A}

$$B_{2A} = \frac{4\pi \times 10^{-7}}{4\pi} \left[\frac{3(-2\pi \times 10^{-4})(0.452) \angle 0^\circ}{(0.452)^4} - \frac{(-2\pi \times 10^{-4}) \angle 0^\circ}{(0.462)^3} \right]$$

$$B_{2A} = \frac{-2(2\pi) \times 10^{-11}}{(0.452)^3} \angle 0^\circ = \frac{-12.64 \times 10^{-10}}{0.925} \angle 0^\circ$$

$$B_{2A} = -13.66 \times 10^{-10}$$

$$B_A = B_{1A} + B_{2A} = 12.84 \times 10^{-10} \angle 0^\circ - 13.66 \times 10^{-10} \angle 0^\circ$$

$$B_A = -0.82 \times 10^{-10} \angle 0^\circ \text{ weber/ (meter)}^2$$

$$B_A = -0.82 \times 10^{-6} \text{ gauss}$$

$$= -0.082 \text{ gamma}$$

$$\text{This is } \frac{0.082}{2.0} = 0.041$$

or 4.1 percent of the specification requirement.



This is also $\frac{0.82 \times 10^{-6}}{13.2 \times 10^{-6}} = 0.0622$

or 6.22 percent of the field caused by a single section choke coil.

It can be seen by inspection that the field disturbance at Pc will be much less because the distances from the coil centers r_1 and r_2 will be identical and hence cancellation will be more perfect. $\cos \theta$ in this case will also be a very small value, since θ_1 and θ_2 are very close to 90° .

It can be concluded from the calculations on the external magnetic field disturbance due to the choke coil that:

- 1) The external magnetic field disturbance of the cup type choke coil with a completely enclosed air gap is 1.32 gamma maximum or 66 percent of the allowable 2 gamma field disturbance at 18 inches.
- 2) If the choke coil is divided into two sections and placed back to back so that the external magnetic fields cancel, the field disturbance can be reduced to 0.032 gamma which is 4.1 percent of the specification requirement. The latter calculations are based upon the assumption that each coil produces an equal and opposite magnetic moment. This will not be the case in practice due to individual differences, and, hence, the magnetic field cancellation will not be as complete as indicated by these calculations.